



Connecticut Transit (CTTRANSIT) Fuel Cell Transit Bus: Third Evaluation Report

Kevin Chandler, Battelle
Leslie Eudy, National Renewable Energy Laboratory

Technical Report
NREL/TP-560-47334-1
January 2010

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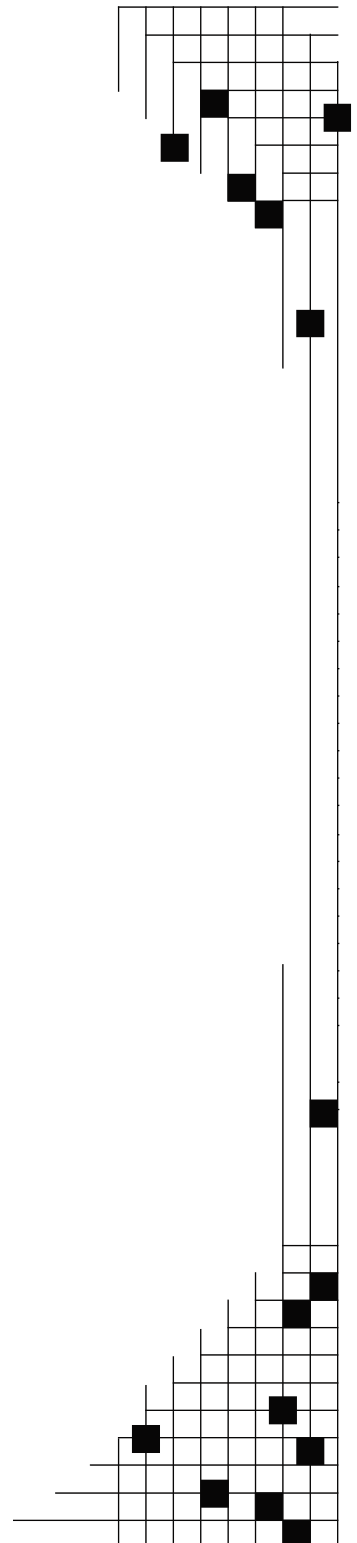
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Acronyms and Abbreviations

CSA	cell stack assembly
DGE	diesel gallon equivalent
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DPF	diesel particulate filter
F	Fahrenheit
ft.	feet
FTA	Federal Transit Administration
gal.	gallon
HVAC	heating, ventilation, and air conditioning
kg	kilogram
kW	kilowatt
MBRC	miles between roadcalls
min	minute
mpg	miles per gallon
mph	miles per hour
NFCBP	National Fuel Cell Bus Program
NREL	National Renewable Energy Laboratory
PMI	preventive maintenance inspection
psi	pounds per square inch
RC	roadcall
SI	International System of Units (metric units)
SOC	state of charge

Executive Summary

This report describes operations at Connecticut Transit (CTTRANSIT) in Hartford for one prototype fuel cell bus and three newer diesel buses operating from the same location. The prototype fuel cell bus was manufactured by Van Hool and ISE Corp. and features an electric hybrid drive system with a UTC Power PureMotion¹ 120 Fuel Cell Power System and ZEBRA batteries for energy storage. The fuel cell bus started operation in April 2007, and evaluation results through October 2009 are provided in this report.

This fuel cell bus is considered prototype technology in the process of being commercialized. The analysis and comparison discussions regarding standard diesel buses help baseline the progress of the fuel cell bus technology. **There is no intent to consider this implementation of fuel cell buses as commercial (or full-revenue transit service).** This evaluation focuses on documenting progress and opportunities for improving the vehicles, infrastructure, and procedures.

The fuel cell transit bus at CTTRANSIT has now had four fuel cell power systems installed since the beginning of operation. Through October 31, 2009, the total fuel cell bus operation at CTTRANSIT has included 31 months, 38,461 miles, and 5,940 hours using three different fuel cell power systems in the bus.

Demonstration Achievements and Challenges

CTTRANSIT's original goal was to operate this prototype fuel cell bus in revenue service for at least two years. CTTRANSIT's location provided an opportunity to evaluate how this design works in a cold and sometimes snowy environment. CTTRANSIT has now operated the bus for almost three years, providing an excellent test-bed for the manufacturers to further optimize the system to increase reliability and durability. Significant achievements have been made during this evaluation, including safe operation and fueling, maintenance facility modifications at a modest/low cost, training CTTRANSIT mechanics to maintain the bus, and increasing public awareness of the bus and the demonstration project.

The primary challenges for operating advanced-technology buses in a transit application are cost and reliability/durability. CTTRANSIT and its project partners have worked closely to address issues encountered and to develop solutions that have moved the technology closer to commercialization. The close proximity of UTC Power headquarters has made this collaboration particularly effective, allowing the manufacturer easy access to a bus for testing modifications that can then be verified and rolled out to the fuel cell buses in California. The greatest challenges for this demonstration have been with the reliability and durability of the bus, which involved traction battery issues and fuel cell power system issues.

Evaluation Results

Table ES-1 provides a summary of results for several categories of data presented in this report—operation between December 2008 and October 2009. This 11-month period was chosen to coincide with the operation of the third fuel cell power system installed in the fuel cell bus. The fourth fuel cell power system was installed at the end of this evaluation period (October 26,

¹ PureMotion is a trademark of UTC Power.

2009). Note that the maintenance costs are high for the fuel cell bus because of the amount of participation by the CTTRANSIT mechanics in fuel cell and hybrid propulsion maintenance. These costs were not charged back to the manufacturers as warranty.

Table ES-1. Summary of Evaluation Period Results

Data Item	Fuel Cell	Diesel
Number of Buses	1	3
Data Period	12/08–10/09	12/08–10/09
Number of Months	11	11
Total Mileage in Period	13,862	112,328
Total Fuel Cell Hours	2,140	N/A
Average Monthly Mileage per Bus	1,260	3,420
Average Operating Speed (mph)	6.5	12
Availability (Target is 85%)	62%	N/A ^a
Fuel Economy (Miles/kg)	4.78	N/A
Fuel Economy (Miles/DGE ^b)	5.40	3.88
Miles Between Roadcalls—All	1,155	16,121
Miles Between Roadcalls—Propulsion Only	1,260 ^c	18,808
Total Maintenance, \$/Mile ^d	1.29	0.40
Maintenance—Propulsion Only, \$/Mile	1.12	0.07

a. Availability for diesel buses not collected—data were not available.

b. Diesel gallon equivalent.

c. For fuel cell propulsion only, Miles Between Roadcalls (MBRC) was 6,931.

d. Work-order maintenance cost.

What's Next for CTTRANSIT?

CTTRANSIT plans to operate this fuel cell bus as long as possible although the agency's primary focus will transition to the new fuel cell bus project under the FTA's National Fuel Cell Bus Program (NFCBP). Under this project, CTTRANSIT will operate up to four new fuel cell buses from Van Hool and UTC Power. NREL will continue to evaluate fuel cell bus operations at this site under funding from FTA and as part of the NFCBP. This is the last planned evaluation report under DOE funding for this fuel cell bus at CTTRANSIT.

To prepare for the arrival of new fuel cell buses, CTTRANSIT has been working with the state to design and construct a new storage building at their depot to be completed around mid-2010. CTTRANSIT has also secured funding through a DOE Clean Cities grant to build a new hydrogen station at the Hartford Division capable of dispensing 30 kg/day of hydrogen on-site in Hartford, Connecticut.

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Introduction

Connecticut Transit (CTTRANSIT)² has been operating one fuel cell bus in revenue service in Hartford, Connecticut, since April 2007. The early operation of this bus has been documented in two previous reports from the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL)^{3,4}. This report continues the evaluation of the fuel cell bus and three diesel buses as a baseline.

NREL Evaluations

NREL has been evaluating alternative fuel and advanced propulsion transit buses for DOE and the Federal Transit Administration (FTA) since the early 1990s. NREL first evaluated hydrogen fuel cell transit buses for DOE in 2000 and continues with this evaluation at CTTRANSIT. These evaluations are focused on determining the status of hydrogen and fuel cell systems and corresponding infrastructure in transit applications to assess the progress toward technology readiness. NREL uses a standard data-collection and analysis protocol originally developed for DOE heavy-duty vehicle evaluations, and a joint evaluation plan has been documented for fuel cell transit bus evaluations⁵. Appendix A describes NREL's transit bus evaluation activities for DOE and FTA.

Fuel Cell Bus Evaluation at CTTRANSIT

CTTRANSIT provides fixed-route transportation services to three major metropolitan areas in the state: Hartford, New Haven, and Stamford. The Hartford Division is the largest of the three areas, operating a total of 237 buses over 30 local routes and 12 express routes in and around the capital area. CTTRANSIT has been investigating new technologies and fuels for its fleet that are more efficient and produce fewer emissions. Appendix B provides more information on CTTRANSIT.

In April 2007, CTTRANSIT began demonstrating one prototype fuel cell bus manufactured by Van Hool and ISE Corp. The prototype fuel cell bus features an electric hybrid drive system with a UTC Power PureMotion⁶ 120 Fuel Cell Power System and ZEBRA batteries for energy storage. This bus was purchased based on the Alameda-Contra Costa Transit District (AC Transit) fuel cell bus order. AC Transit operates three fuel cell buses nearly identical to the one at CTTRANSIT. There is only one other fuel cell bus of this design operating in the U.S., and it operates at SunLine Transit Agency. NREL has been evaluating all three locations operating these Van Hool/ISE Corp./UTC Power fuel cell buses. The CTTRANSIT fuel cell bus is shown in Figure 1.

² CTTRANSIT Web site: www.cttransit.com.

³ CTTRANSIT, *Fuel Cell Transit Bus: Preliminary Evaluation Results*, October 2008, NREL/TP-560-43847, www.nrel.gov/hydrogen/pdfs/43847.pdf.

⁴ CTTRANSIT, *Fuel Cell Transit Bus: Second Evaluation Report and Appendices*, May 2009, NREL/TP-560-45670-1 and NREL/TP-560-45670-2, www.nrel.gov/hydrogen/pdfs/45670-1.pdf and www.nrel.gov/hydrogen/pdfs/45670-2.pdf.

⁵ Hydrogen and Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration, NREL/MP-560-42781, May 2008, www.nrel.gov/hydrogen/pdfs/42781-1.pdf.

⁶ PureMotion is a trademark of UTC Power.



Figure 1. CTTRANSIT fuel cell bus

Three diesel buses operating from the same location as the fuel cell bus have been selected to use as a baseline comparison. These diesel baseline buses, shown in Figure 2, are 40-ft New Flyer buses with Cummins ISL engines. These diesel buses use some of the first model year 2007 diesel ISL engines from Cummins, and they have an actively regenerated diesel particulate filter (DPF). Appendix C provides more detail about the bus technologies included in this evaluation.



Figure 2. One of CTTRANSIT's diesel buses (same as those used in evaluation)

CTTRANSIT currently has access to hydrogen at the UTC Power headquarters, about seven miles away. The UTC Power fueling station features liquid hydrogen storage and compression. The fuel is vaporized and dispensed into the bus as gaseous hydrogen. The hydrogen, supplied by Praxair from their location near Niagara Falls, is produced renewably as a by-product of a chemical process. CTTRANSIT modified its existing facility to allow for safe storage and minor maintenance of the hydrogen-fueled bus. Appendix D provides more detail about modifications to CTTRANSIT's maintenance and bus storage facilities.

The CTTRANSIT fuel cell bus has been operating in standard service almost exclusively on their Star Shuttle route, which is a downtown loop that operates every 12 minutes. This route is

5.5 miles long and has an average speed of 10 mph. The fuel cell bus is also used for events in Hartford and other locations in the state, and it occasionally has been transported out of state for events.

The diesel buses have continued to operate in normal operation in Hartford (randomly dispatched). The average speed of diesel bus operation at Hartford is 12 mph. This average speed for the diesel buses has been significantly higher than the average speed experienced by the fuel cell bus even though the Star Shuttle route is scheduled at an average speed of 10 mph. During the evaluation period, the fuel cell bus experienced an average speed of 6.5 mph. The primary reason for this lower average speed is that the fuel cell is not shut down when the bus is idle between runs. There are no emission issues as there are with diesel buses, and there is a desire to avoid shutting down the fuel cell system while the bus is out on the route.

What's in this Evaluation Report?

This fuel cell transit bus at CTTRANSIT has now had four fuel cell power systems installed since the beginning of operation. Through October 31, 2009, the total fuel cell bus operation at CTTRANSIT has included 31 months, 38,461 miles, and 5,940 hours using three different fuel cell power systems in the bus.

- The first fuel cell power system operated in the bus from April 2007 (initial start-up of operation) through mid-January 2008 (5,157 miles, 907 hours, 5.7 mph).
- The second fuel cell power system operated from mid-January 2008 until November 24, 2008 (approximately 11 months). This second fuel cell power system was used to attempt to increase operation as much as this implementation would allow. The fuel cell bus was operated on two eight-hour shifts on the Star Shuttle route during weekdays and weekends with some additional operation on other routes during the weekends. This maximum service was discontinued with the replacement of the fuel cell power system in November 2008 (19,442 miles, 2,893 hours, 6.7 mph).
- The third fuel cell system operated from the end of November 2008 through late October 2009 (11 months) and is the focus of this evaluation report (13,862 miles, 2,140 hours, 6.5 mph).
- A fourth fuel cell power system was installed at the end of this report's evaluation period: October 26, 2009. (Note: UTC Power installed this stack to test newer technology in service. The stack removed was not experiencing end of life issues—it was transferred to another site and is still in use.)

An overview of the accomplishments and challenges of this fuel cell bus demonstration is provided first. The data analysis in this evaluation report is focused on an 11-month period of fuel cell bus operation with the third installment of a fuel cell power system from UTC Power—December 2008 through October 2009. Some results from the entire operating experience (31 months) are also provided.

Demonstration Achievements and Challenges

CTTRANSIT and its partners have gained valuable experience from operating the fuel cell bus in service. This section summarizes the achievements and challenges of the demonstration period while pointing to lessons learned for each.

Achievements

CTTRANSIT's original goal was to operate this prototype fuel cell bus in revenue service for at least two years, working closely with the manufacturers to test and evaluate fuel cell technology in a transit application. The project team worked closely to understand the needs for transit service and to investigate what modifications would be required to commercialize the technology. CTTRANSIT's location also provided an opportunity to evaluate how this design works in a cold and sometimes snowy environment. Since the start of service, CTTRANSIT has operated the bus for almost three years, providing an excellent test-bed for the manufacturers to further optimize the system to increase reliability and durability.

- **Bus Operation** – The fuel cell bus went into service in April 2007. Through October 2009, the bus had operated over 38,000 miles and accumulated over 5,900 hours on the fuel cell system.
- **Fuel Economy** – CTTRANSIT's fuel cell bus achieved an average fuel economy of 4.79 miles per kg (12.97 kg hydrogen/100 km), which is lower than that of similar buses in service in California, which have achieved fuel economies of over 7 miles per kg (8.7 kg hydrogen/100 km). This difference shows how duty-cycle can have a significant effect on fuel economy. Operating primarily on CTTRANSIT's Star Shuttle Route results in much lower average speeds and higher idle time for this fuel cell bus. The fuel economy of the CTTRANSIT fuel cell bus equates to 5.4 miles per diesel equivalent gallon, which is 47% higher than the diesel baseline bus average of 3.68 mpg.
- **Hydrogen** – CTTRANSIT fuels its bus at UTC Power's hydrogen station a few miles away. The UTC Power fueling station features liquid hydrogen storage, compression, and dispensing. The hydrogen is produced in western New York as a by-product of a chemical process. Both the chemical process that produces the hydrogen and the purification stage are powered utilizing hydropower from Niagara Falls. Other than the delivery method (by truck), this project is fueled by renewable hydrogen. The cost per kg of the fuel is also lower than that of most other demonstration projects.
- **Fueling** – During the demonstration, the fuel cell bus has been safely fueled 352 times, using nearly 8,000 kg of hydrogen.
- **Maintenance Facility Modifications** – Gaining approval to bring the fuel cell bus into its existing garage was accomplished with relative ease. At the onset of the project, CTTRANSIT hired a consultant to investigate what modifications were necessary to enable a hydrogen vehicle to be operated, maintained, and parked in the facility. Recommendations from the consultant included minor modifications, which cost the agency only \$150,000 (including the consultant's fee). CTTRANSIT worked closely with local fire officials early in the process and was not required to make extensive

electrical or ventilation upgrades. This fuel cell bus design includes the ability to move the bus on electric power only—the hydrogen and fuel cell system is temporarily disabled. Because of this, the required upgrades were simple and inexpensive, and the fuel cell bus must be operated in electric-only mode while inside the facility. For past fuel cell bus projects, this has been one of the most challenging aspects of the demonstration. CTTRANSIT's ease in accomplishing this portion of the project is a striking contrast to other transit agency experience.

- **Training** – The agency took advantage of opportunities to learn from other early adopters of the technology, specifically AC Transit. Training for staff and local officials has been particularly important for CTTRANSIT, and it was initiated prior to arrival of the bus. CTTRANSIT and its project partners organized a comprehensive training program to provide hydrogen familiarization and detailed maintenance and operations information for the fuel cell bus to the appropriate staff. The two senior-level technicians assigned to work on the fuel cell bus conduct much of the hybrid system repairs (including warranty work for ISE) and actively participate in fuel cell system work. The agency thought hands-on experience with the new technology was very important, and the technicians were willing to do as much of the work as the manufacturers would allow. This is a major step toward the goal of transferring all maintenance to agency staff.
- **Public Awareness** – CTTRANSIT reports a high level of interest in the fuel cell bus demonstration from the local community and the region. The agency receives requests to demonstrate the bus at various events and accommodates as many as possible. The agency specifically chose to operate the bus on its Star Shuttle Route to showcase the technology. This route offers free service around downtown Hartford, connecting hotels with the convention center, restaurants, and many other landmarks. This downtown route has been extremely conducive to having visitors ride the bus in service without disrupting CTTRANSIT staff and operations. The agency also conducted a passenger survey to determine the level of awareness and acceptance for fuel cell bus technology in the Hartford area. Results showed a high level of interest in the technology, and passengers ranked the fuel cell bus performance much higher compared with conventional diesel buses.

Challenges

The primary challenges for operating advanced-technology buses in a transit application are cost and reliability/durability. CTTRANSIT and its project partners have worked closely to address any issues encountered and to develop solutions that will move the technology closer to commercialization. The close proximity of UTC Power headquarters has made this collaboration particularly effective, allowing the manufacturer easy access to a bus for testing modifications that can then be verified and rolled-out to the fuel cell buses in California.

- **Costs** – Fuel cell buses are following the typical trend of all prototype technology: capital costs are high in the early stages and begin to fall with increased production and further product development. The operating costs are also higher than that of conventional technology.

- **Fuel cell bus reliability/durability** – The manufacturers are working with demonstration partners to increase the reliability and durability of fuel cell buses to meet transit requirements. Several issues were encountered during the demonstration primarily with the traction batteries and the fuel cell system. These issues were also encountered at the other demonstration sites for this bus.
 - **Traction Battery Issues** – Management of the ZEBRA batteries in this design has proved to be the biggest challenge. The hybrid design on the bus includes three traction batteries operating in parallel. A cell in a ZEBRA battery typically will fail in short circuit. A battery with failed cells has reduced voltage even though it still can be operated. Because the batteries operate with a direct parallel connection, when the number of failed cells within each of the batteries is too different among the three batteries, the difference causes an unbalancing of the state of charge (SOC). This imbalance makes it difficult to keep the batteries in the recommended operating range. The present SOC balancing algorithm will disconnect a battery temporarily to keep the SOC balanced.

This situation may mislead over-volt errors in the propulsion system, causing a bus shutdown. UTC Power has been working closely with the battery manufacturer (MES-DEA) on the issue for some time. Because failed cells are related to a stress condition due to the battery use, some progress has been made with controller software changes to improve battery operation by refining some operational limits. Options for a balancing strategy are under discussion. More replacement batteries are kept in stock to increase the number of available better-matched batteries and to reduce the amount of downtime of the fuel cell bus. MES-DEA also provided training at CTTRANSIT that was extremely helpful to the project team. The manufacturer has provided a manual that includes information and fault code definitions. This has been extremely helpful in understanding the battery and systems and how to troubleshoot and diagnose problems.
 - **Fuel Cell System Issues** – UTC Power monitors the performance of the fuel cell power system to analyze actual performance versus predicted performance. Early on in the demonstration, the cell stack assemblies (CSAs) showed power degradation in the operation of the bus. When the power degradation of the CSAs falls below 90 kW to 100 kW of the original 120 kW, the system is considered to be at the end of its life and should be replaced. This early power degradation was reported with the fuel cell buses at other agencies as well, and UTC Power reports the problem as an issue of contamination within the CSAs causing the premature degradation beyond end of life (at about 800 to 1,200 hours of operation instead of the expected 4,000 hours or more). A new version of CSAs replaced the CSAs on the fuel cell buses at each of the agencies. UTC Power reported that this early power-degradation issue was resolved for these buses.
- **Air-Conditioning Noise** – Hybrid electric propulsion systems in transit buses tend to be extremely quiet compared with conventional buses. This has resulted in other “noises” within the bus becoming more noticeable. Early on in the operation of this fuel cell bus, the air-conditioning fans were noticeably loud. UTC Power engineers set out to quiet the air

conditioning by adding baffling and other fixes to the system. The air conditioning on the bus is significantly quieter now.

- **Operating in Slippery Conditions** – The electric propulsion system on the fuel cell bus has some issues with slipping in snowy or icy conditions. This has caused a significant problem with operation of the bus only a few times since the start of operations. ISE continues to study the issue and is considering a software change to the operation of the bus but is not yet drawing any conclusions.
- **Fueling Time** – Although the hydrogen station at UTC Power is within seven miles, the lack of fueling at the agency facility increases the time to fuel and therefore the operating cost. Agency staff must drive the bus to the location, wait for the fueling process to be completed, and then drive the bus back to the depot.

Hydrogen Fueling Experience

When the fuel cell bus needs hydrogen, a CTTRANSIT staff member drives it to the UTC Power facility, which is about seven miles northeast of the bus depot. The station is located behind locked gates in a secure area of the UTC Power property. The bus driver calls ahead to ensure that trained staff are available to provide access to this secure area and to operate the station. At this point in the demonstration, only trained UTC Power employees fuel the bus.

Early in the project, the process for fueling the bus took approximately one hour. This time was due mainly to procedures developed for safety, which included placing traffic cones to block other vehicle access, hooking up, and dispensing fuel. The length of the process was also sometimes due to station start-up time. The time needed to drive the bus to and from the site required significant resources from the transit agency. As the project partners have become more comfortable with the fueling process, UTC Power has streamlined the procedures and reduced fueling times to approximately 30 minutes.

Figure 3 shows the monthly total hydrogen use by CTTRANSIT's fuel cell bus. The fuel usage was low during February through May 2009, which was caused by problems with the electric propulsion system. A wiring harness was replaced, and the traction batteries were replaced in May 2009 before starting full planned service again in June 2009.

Figure 4 shows the distribution of hydrogen amounts per fill. The fuel cell bus was filled 134 times with a total of 2,899 kg of hydrogen during the evaluation period, which is an average fill amount of 21.6 kg. Total hydrogen usage of the fuel cell bus since the beginning of operation (April 2007 through October 2009) includes 7,984 kg of hydrogen in 352 fuelings and an average fill amount of 22.7 kg.

Figure 5 shows the number of fueling events and average time per fill per month. The average fueling time was 33.4 minutes during the evaluation period. Note that the fueling time includes the time required to set up safety measures around the fueling station to keep other vehicles out of the area. For all operation (April 2007 through October 2009), the average fill time was 32.0 minutes.

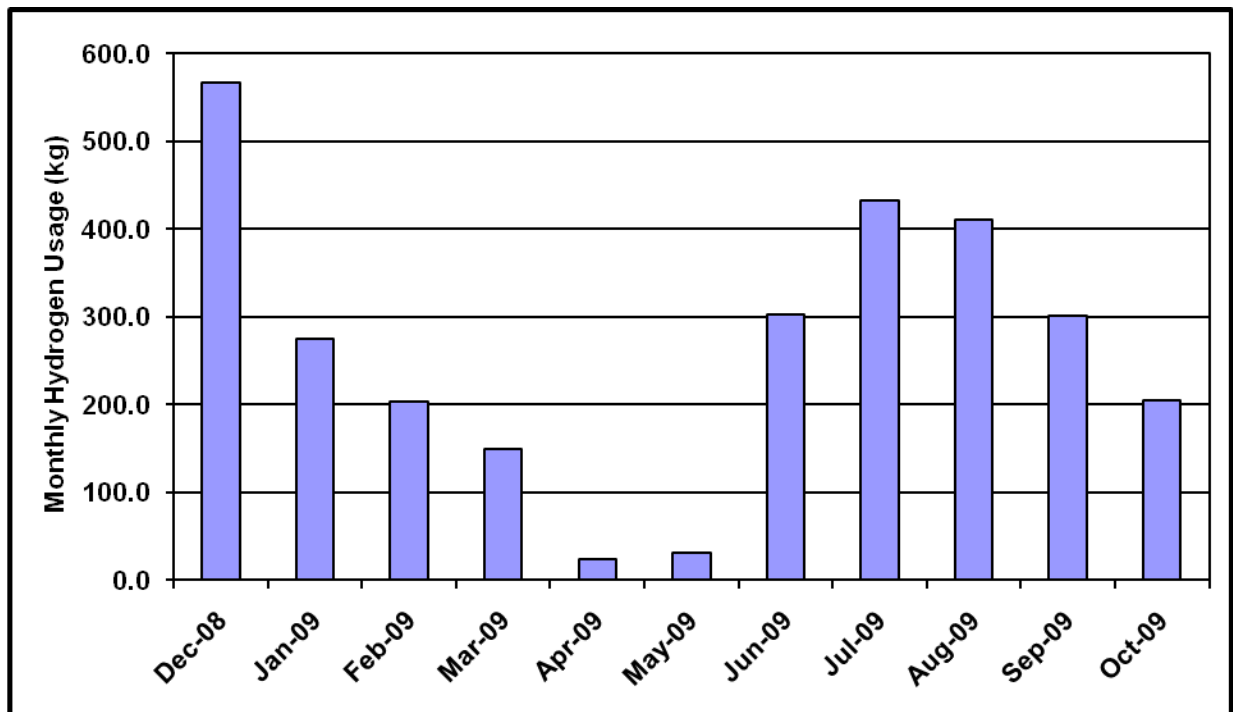


Figure 3. Monthly total hydrogen use by CTTRANSIT's fuel cell bus

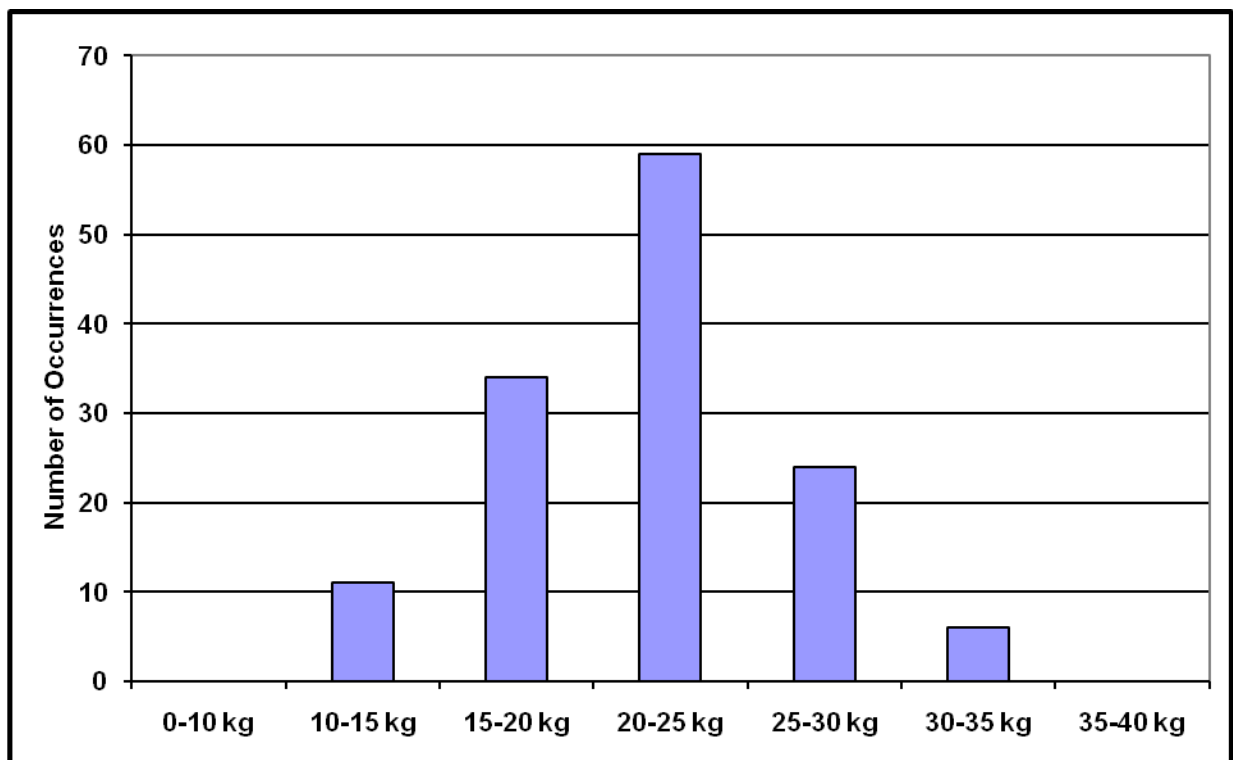


Figure 4. Distribution of average fill amounts for the fuel cell bus

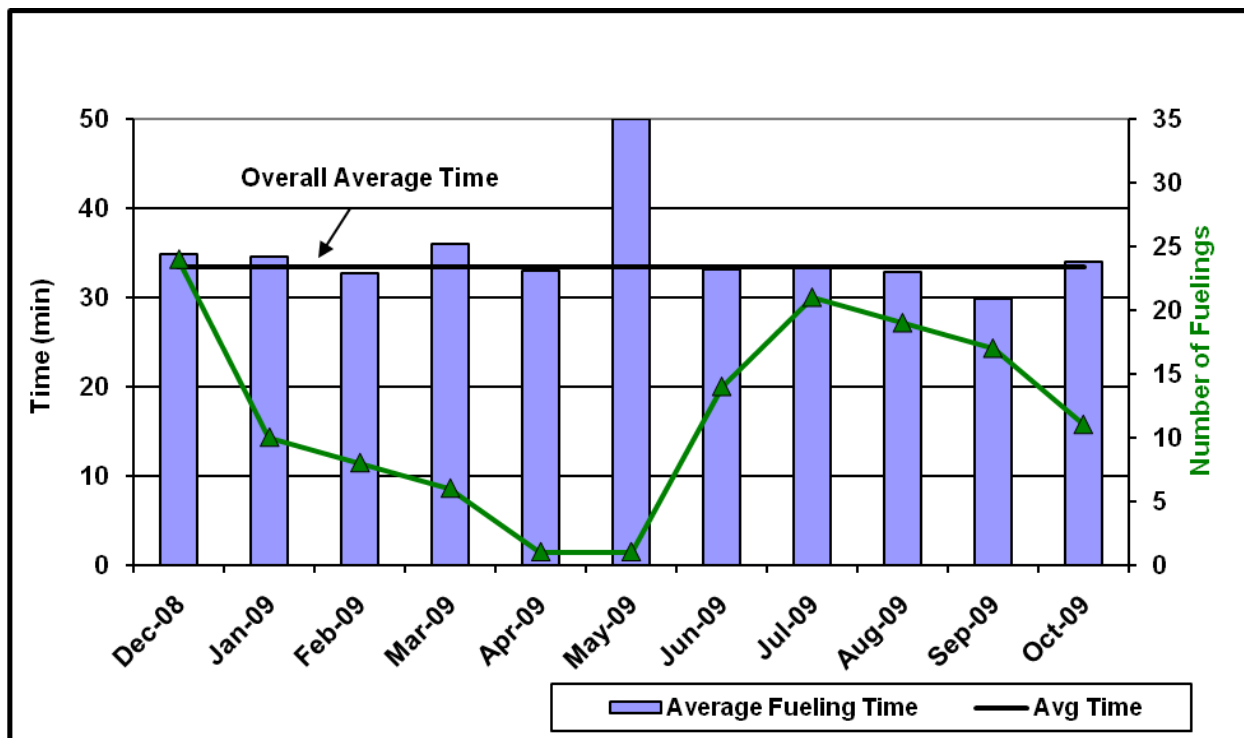


Figure 5. Average time per fueling and number of fueling events per month

Evaluation Results

The evaluation period presented in this report includes operation of the fuel cell and diesel baseline buses from December 2008 through October 2009 (11 months). As discussed above, this evaluation period was selected to match the operation of the third installment of the fuel cell power system. In this evaluation, the fuel cell bus is considered prototype technology in the process of being commercialized. The analysis and comparisons with standard diesel buses help create a baseline for measuring the progress of the fuel cell bus technology. **There is no intent to consider this implementation of fuel cell buses as commercial (or full-revenue transit service).** This evaluation focuses on documenting progress and opportunities for improving the vehicles, infrastructure, and procedures. A full summary of the evaluation results is provided in Appendix E, and a summary of results in SI (metric) units is provided in Appendix F.

Fuel Cell Bus Operation

The fuel cell bus at CTTRANSIT has been operating in service in the Hartford, Connecticut, area since April 2007, and evaluation results are reported here through October 31, 2009. This section provides evaluation results for the newest operations period of December 2008 through October 2009 (11 months) along with some summary evaluation results for the entire demonstration of April 2007 through October 2009 (31 months).

As mentioned above, this fuel cell bus has been operated almost exclusively on the Star Shuttle route, which has an average speed of nearly 10 mph; however, the fuel cell bus is not shut down at layover points. This has caused the fuel cell bus operating speed to be 6.5 mph during the evaluation period. This is much lower than the diesel baseline/comparison buses at 12 mph. This

causes some issues with comparing bus usage and fuel economy, which will be discussed later in this section.

During the evaluation period, the fuel cell bus has been operated on weekdays on the Star Shuttle route for two eight-hour shifts. The fuel cell bus is plugged in each night to recharge the traction batteries. A full charge for the traction batteries requires between 4 and 4.5 hours. During bus operation on the route, the batteries are kept at 50% to 60% SOC to allow for significant energy regeneration from braking back into the batteries.

Bus Use and Availability

Bus use and availability are indicators of reliability. Lower bus usage could indicate downtime for maintenance or an intentional reduction of planned work for the buses. This section provides a summary of bus usage and availability for the two groups studied.

Table 1 summarizes the average monthly mileage accumulation by the fuel cell bus and the diesel study group for the evaluation period. During this period, the fuel cell bus accumulated 13,862 miles, and the fuel cell system accumulated 2,140 hours. These numbers indicate an overall average speed of 6.5 mph, which is significantly slower than the average CTTRANSIT speed of 12 mph and the 10-mph Star Shuttle route average.

The diesel buses operated a monthly average of 3,420 miles each as compared to the fuel cell bus, which had a monthly average of 1,260 miles. This indicates that the fuel cell buses traveled only 37% of the miles that the diesel buses did during the same period.

Table 2 summarizes the average monthly mileage accumulation by the fuel cell bus and the diesel study group for the entire data period. During this period, the fuel cell bus accumulated 38,461 miles, and the three fuel cell power systems accumulated 5,940 hours. These numbers indicate an overall average speed of 6.5 mph. The diesel buses operated a monthly average of 3,305 miles each as compared to the fuel cell bus, which had a monthly average of 1,241 miles. This indicates that the fuel cell buses traveled only 37% of the miles that the diesel buses did during the same period.

Table 1. Average Monthly Mileage (Evaluation Period)

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average Mileage	Fuel Cell System Hours
FCB/701	24,530	38,392	13,862	11	1,260	2,140
725	50,701	88,213	37,512	11	3,410	N/A
726	48,532	86,815	38,283	11	3,480	N/A
727	51,793	88,847	37,054	11	3,369	N/A
Diesel			112,849	33	3,420	N/A

Table 2. Average Monthly Mileage (Entire Data Period)

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average Mileage	Fuel Cell System Hours
FCB/701	N/A	38,392	38,461	31	1,241	5,940
725	2,112	88,213	86,101	26	3,312	N/A
726	2,201	86,815	84,614	26	3,254	N/A
727	1,745	88,847	87,102	26	3,350	N/A
Diesel			257,817	78	3,305	N/A

Another measure of reliability is availability—the percent of days that a bus is actually available compared to the days the bus is planned for operation. Figure 6 shows monthly availability for the fuel cell bus during the evaluation period. Most of the availability issues were due to problems with the traction batteries and the hybrid propulsion and hydrogen fuel system. Overall availability for the fuel cell bus during the evaluation period was 62%. The overall availability for the fuel cell bus during the entire data period was 64%.

Figure 7 shows the uses of the fuel cell bus when it was available for service during the evaluation period. This bus was used 98% of the time on route in service and 2% in support of event activities. Figure 8 shows the reasons why the bus was unavailable for service. The primary reasons for unavailability are for the ISE hybrid propulsion system at 72%, problems with the ZEBRA/traction batteries at 18%, and issues with the UTC Power fuel cell system at 8%.

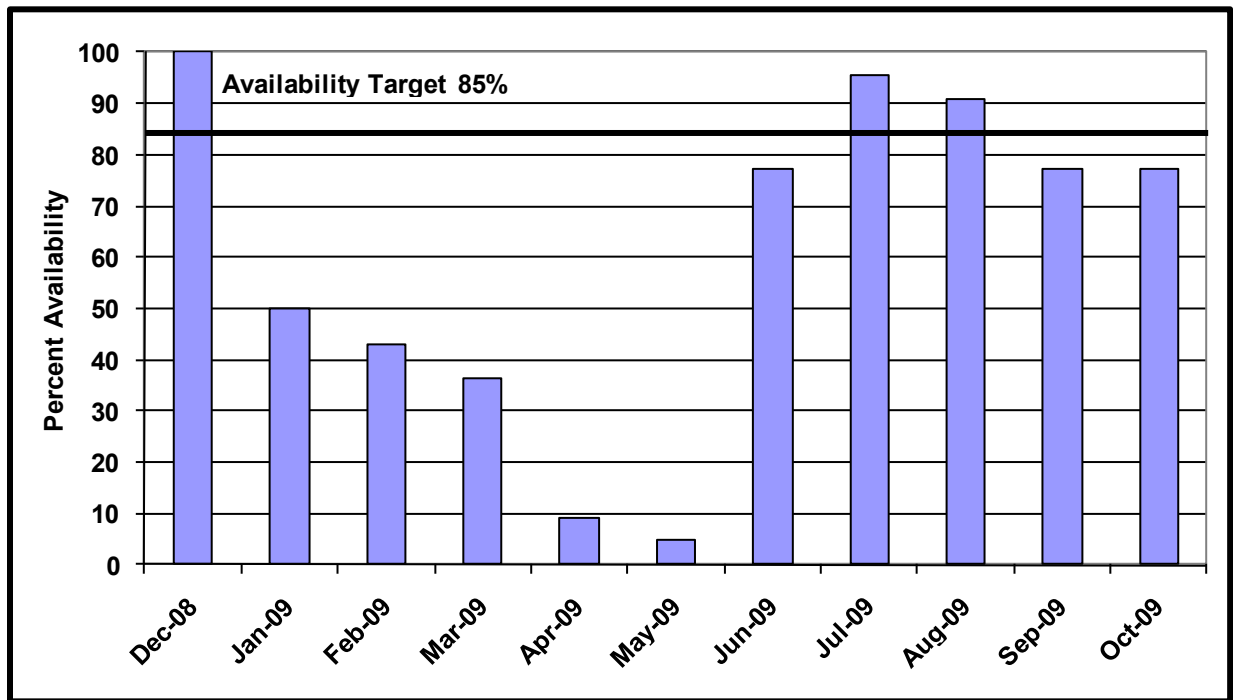


Figure 6. Availability for the fuel cell bus (evaluation period)

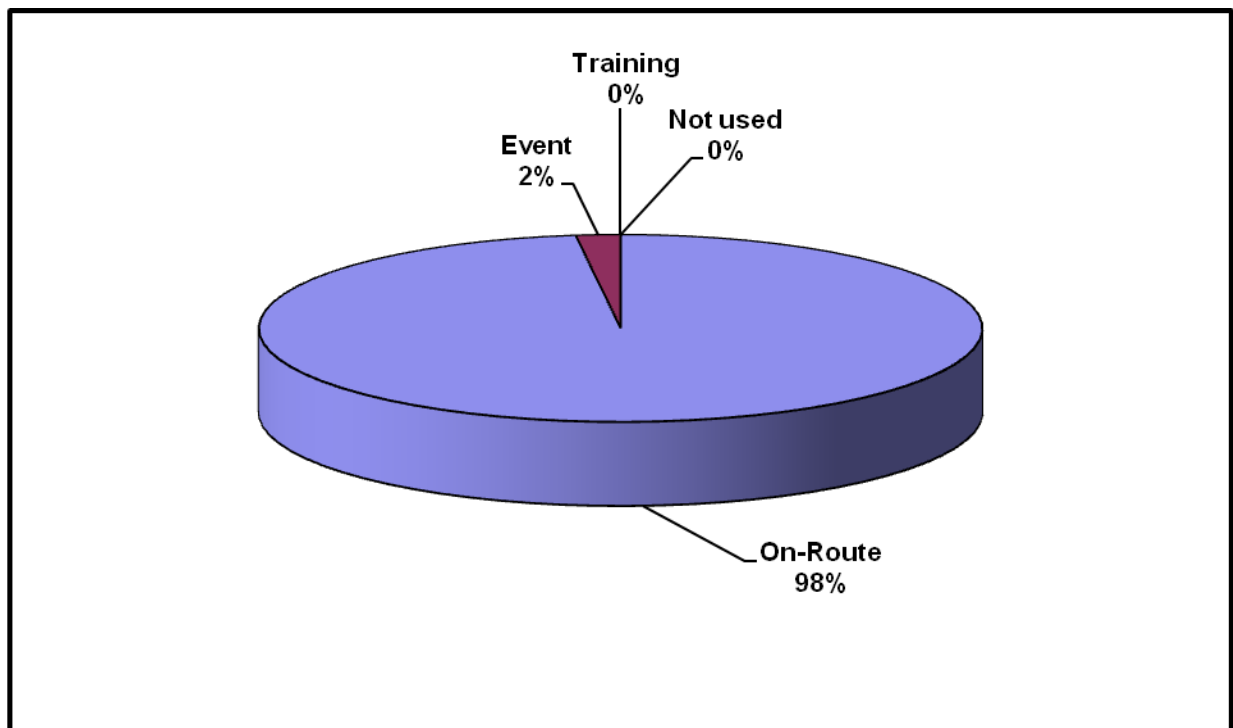


Figure 7. Use of the fuel cell bus when available for service (evaluation period)

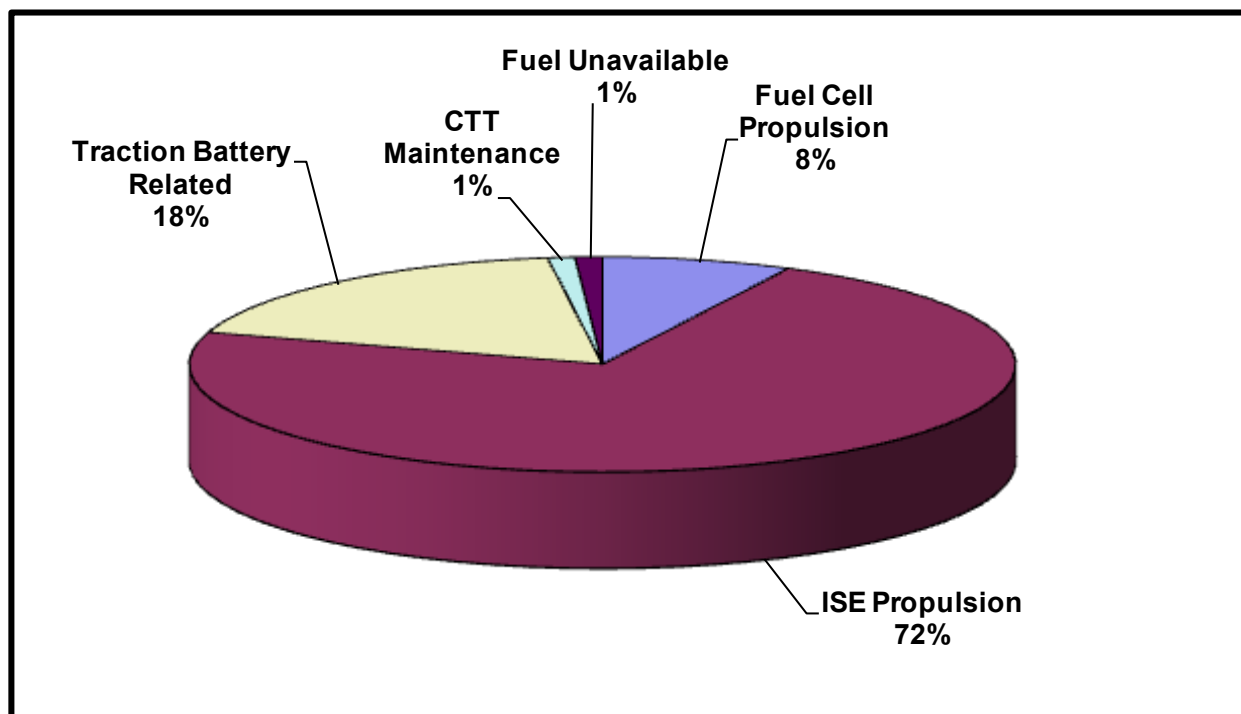


Figure 8. Reasons why the fuel cell bus was unavailable (evaluation period)

Fuel Economy and Cost

Hydrogen fuel is supplied by the UTC Power fueling station (discussed above). The hydrogen is dispensed at up to 5,000 psi for the fuel cell transit bus. During the evaluation period, UTC Power employees provided all fueling services, and fueling data were recorded by CTTRANSIT.

Table 3 shows hydrogen and diesel fuel consumption and fuel economy for the study buses during the evaluation period. Overall, the fuel cell bus averaged 4.78 miles per kg of hydrogen, which equates to 5.40 miles per diesel gallon equivalent (DGE). The energy conversion from kg of hydrogen to DGE is provided at the end of Appendix E. As noted above, the buses are plugged in each night to recharge the batteries. The electric energy added to the fuel cell buses each night currently is not accounted for in the fuel economy calculation⁷.

Table 3. Fuel Use and Economy (Evaluation Period)

Bus	Mileage (Fuel Base)	Hydrogen (kg)	Miles per kg	Diesel Equivalent Amount (gallon)	Miles per Gallon (mpg)
FCB 701 Total	13,862	2,899.5	4.78	2,566	5.40
725	37,348			9,506	3.93
726	38,118			9,780	3.90
727	36,862			9,654	3.82
Diesel Total	112,328			28,940	3.88

For the evaluation period, the three diesel baseline buses averaged 3.88 mpg, which indicates the fuel economy for the fuel cell bus is an overall 39% higher than that of the diesel buses. Note that the diesel buses operate at an average speed of approximately 12 mph, and the fuel cell bus had a measured average speed of 6.5 mph during the evaluation period.

Table 4 shows hydrogen and diesel fuel consumption and fuel economy for the study buses for the entire data period. Overall, the fuel cell bus averaged 4.79 miles per kg of hydrogen, which equates to 5.41 miles per DGE. The three diesel baseline buses averaged 3.68 mpg, which indicates the fuel economy for the fuel cell bus is an overall 47% higher than that of the diesel buses.

Table 4. Fuel Use and Economy (Entire Data Period)

Bus	Mileage (Fuel Base)	Hydrogen (kg)	Miles per kg	Diesel Equivalent Amount (gallon)	Miles per Gallon (mpg)
FCB 701 Total	38,065	7,945	4.79	7,031	5.41
725	86,565			23,094	3.75
726	84,899			23,288	3.65
727	86,850			23,820	3.65
Diesel Total	258,314			70,202	3.68

Figure 9 shows the average monthly fuel economy in both miles per kg and miles per DGE for the fuel cell bus and in miles per gallon for the diesel buses. For reference, the chart also shows the average monthly high and low temperatures. The peak fuel economy for the fuel cell bus in April 2009 represents only one fueling in that month and is not representative of the average fuel economy for the bus. January and February 2009 have fuel economies slightly lower than most of the remaining data period. These fuel economies were affected by a hydrogen fuel leak on the bus during that time frame.

⁷ An additional study has been completed at AC Transit to estimate the amount of energy consumed in the recharging process and the impact on the fuel economy calculation. Results from that effort indicate that the charging energy accounts for up to 5% of the total energy consumed by the bus.

The operating cost for the UTC Power hydrogen production and dispensing is currently unknown; however, the current cost of fuel charged by UTC Power is \$5.29/kg. This amount does not include all the costs of purchasing, transporting, and dispensing the fuel. During the evaluation period, CTTRANSIT spent 183 hours of mechanic time driving the fuel cell bus to and from UTC Power for fueling. This cost is not included in the price of fuel, but it would add another \$0.66 per mile based on a \$50-per-hour labor rate. Using the \$5.29-per-kg cost for hydrogen fuel indicates that the cost per mile for the fuel cell bus is \$1.11, and adding the labor brings it to \$1.77 per mile. The average diesel fuel cost during the evaluation period is \$2.70 per gallon. CTTRANSIT locked into this fixed cost for 12 months, which included the evaluation period. The diesel fuel cost per mile was \$0.70, or less than half the fuel cell bus fueling cost per mile.

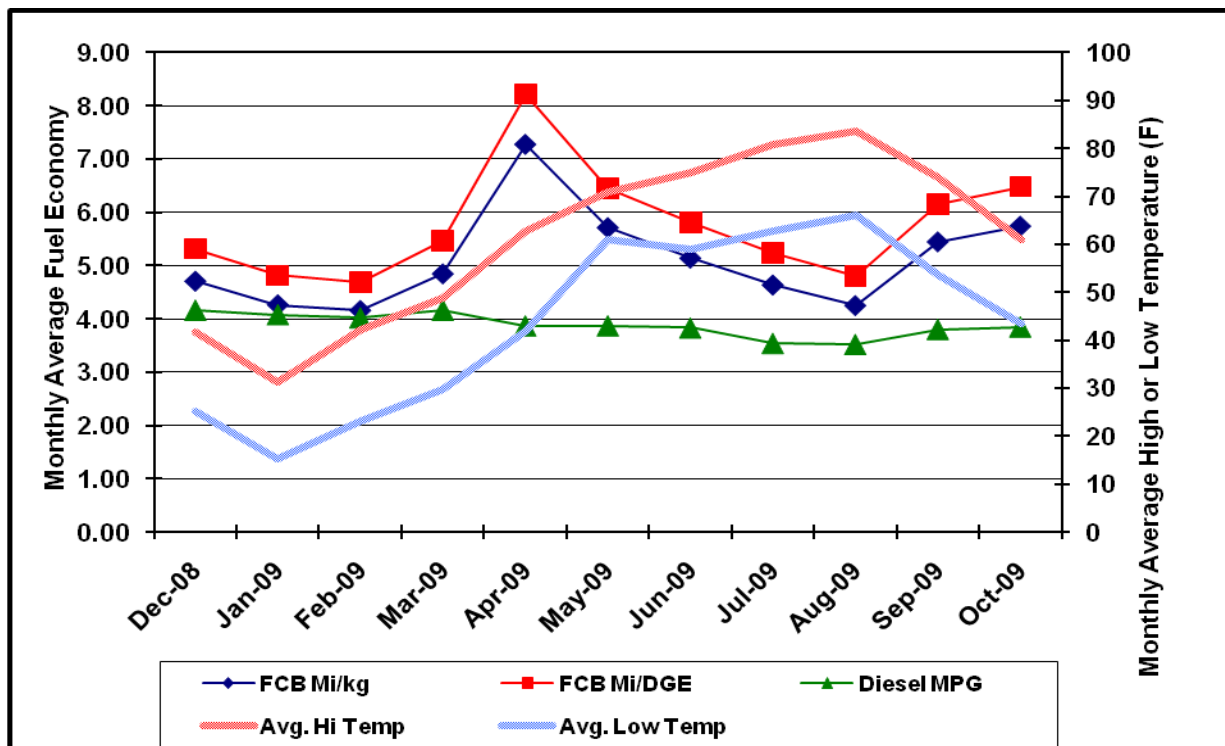


Figure 2. Average monthly fuel economy (evaluation period)

Maintenance Analysis

The maintenance cost analysis presented here includes only the evaluation period (December 2008 through October 2009). Warranty costs are not included in the cost-per-mile calculations. All work orders for the study buses were collected and analyzed for this evaluation. For consistency, the maintenance labor rate was kept at a constant \$50 per hour; this does not reflect an average rate for CTTRANSIT. This section first covers total maintenance costs and then provides maintenance costs separated by bus system.

Total Maintenance Costs – Total maintenance costs include the price of parts and labor rates of \$50 per hour; this total does not include warranty costs. Cost per mile is calculated as follows:

$$\text{Cost per mile} = [(\text{labor hours} * \$50/\text{hr}) + \text{parts cost}] / \text{mileage}$$

Table 5 shows total maintenance costs for the fuel cell and diesel buses for the evaluation period. Note that the fuel cell bus maintenance costs shown in the table are three times higher. This higher cost indicates the level of maturity of the technology and the amount of on-site warranty work done by the CTTRANSIT mechanics. The mechanic labor costs for taking the fuel cell bus to and from fueling at UTC Power are not included here. Table 6 shows total maintenance costs for the fuel cell and diesel buses for the entire data period. Note that the maintenance for the fuel cell bus has become much more efficient over time. The maintenance cost for the fuel cell bus in the evaluation period is almost half the cost in the entire data period.

Table 5. Total Maintenance Costs (Evaluation Period)

Bus	Mileage	Parts (\$)	Labor Hours	Cost per Mile (\$)
Total Fuel Cell 701	13,862	3,160.18	294.6	1.29
725	37,512	3,453.88	198.5	0.36
726	38,283	5,436.06	222.2	0.43
727	37,054	4,401.46	210.2	0.40
Total Diesel	112,849	13,291.40	630.8	0.40
Avg. per Bus	37,616	4,430.47	210.3	--

Table 6. Total Maintenance Costs (Entire Data Period)

Bus	Mileage	Parts (\$)	Labor Hours	Cost per Mile (\$)
Total Fuel Cell 701	38,461	6,098.35	1,526.2	2.14
725	86,729	11,368.57	541.7	0.44
726	85,409	8,757.70	461.0	0.37
727	87,409	8,422.00	435.9	0.35
Total Diesel	259,547	28,548.27	1,438.5	0.39
Avg. per Bus	86,516	9,516.09	479.5	--

As discussed previously, maintenance issues for the fuel cell bus centered on problems with the traction batteries and on-board battery charger, change out of a wiring harness, a hydrogen fuel leak in the on-board fuel storage system, and the replacement of the fuel cell system. Most of the repair costs were to support troubleshooting and repairs for the heating, traction battery changeouts and replacement of battery management hardware, and support to UTC Power for changing the fuel cell power system.

Maintenance issues for the diesel buses included three brake relines, a problem with hydraulic lines being replaced, issues with the air conditioning, body damage, and the engine.

The total maintenance costs—excluding warranty costs—are much less for the diesel buses. The per-bus results for the fuel cell buses compared with the diesel buses for the evaluation period (Table 5) are as follows.

- Usage/Mileage: The fuel cell bus mileage is 63% lower than that of the diesel buses.
- Parts Costs: The fuel cell bus parts are 36% less than those for the diesel buses.
- Labor Hours: The fuel cell bus labor hours are 40% higher than for the diesel buses.
- Cost per Mile (excluding warranty costs): The fuel cell bus costs are 3.2 times greater than those of diesel buses.

Maintenance Costs Broken Down by System – Table 7 shows maintenance costs by vehicle system and bus study group (excluding warranty costs) for the evaluation period. The vehicle systems shown in the table include the following.

- **Cab, Body, and Accessories:** Includes body, glass, and paint repairs following accidents; cab and sheet metal repairs on seats and doors; and accessory repairs, such as hubodometers and radios.
- **Propulsion-Related Systems:** Includes repairs for exhaust, fuel, engine, electric motors, fuel cell modules, propulsion control, non-lighting electrical (charging, cranking, ignition), air intake, cooling, and transmission.
- **Preventive Maintenance Inspections (PMI):** Includes labor for inspections during preventive maintenance.
- **Brakes**
- **Frame, Steering, and Suspension**
- **Heating, Ventilation, and Air Conditioning (HVAC)**
- **Lighting**
- **Air System, General**
- **Axles, Wheels, and Drive Shaft**
- **Tires**

Table 7. Vehicle System Maintenance Cost per Mile by System (Evaluation Period)

System	Fuel Cell		Diesel	
	Cost per Mile (\$)	Percent of Total (%)	Cost per Mile (\$)	Percent of Total (%)
Cab, Body, and Accessories	0.06	5	0.15	38
Propulsion Related	1.12	87	0.07	18
PMI	0.05	4	0.08	20
Brakes	0.00	0	0.04	10
Frame, Steering, and Suspension	0.03	2	0.01	2
HVAC	0.01	1	0.03	8
Lighting	0.02	1	0.01	2
Air, General	0.00	0	0.00	0
Axles, Wheels, and Drive Shaft	0.00	0	0.00	0
Tires	0.00	0	0.01	2
Total	1.29	100	0.40	100

The systems with the greatest percentage of maintenance costs for the fuel cell bus and diesel buses were propulsion related; PMI; and cab, body, and accessories.

Propulsion-Related Maintenance Costs – Propulsion-related vehicle systems include the exhaust, fuel, engine, electric propulsion, air intake, cooling, non-lighting electrical, and transmission systems. Table 8 shows the propulsion-related system repairs by category for the two study groups during the evaluation period. The maintenance costs do not include the work done by the UTC Power personnel, which was covered under warranty.

Table 8. Propulsion-Related Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	Fuel Cell	Diesel
Mileage	13,862	112,849
Total Propulsion-Related Systems (Roll-Up)		
Parts cost (\$)	2,338.06	4,529.20
Labor hours	262.5	72.3
Total cost (\$)	15,463.06	8,141.70
Total cost (\$ per mile	1.12	0.07
Exhaust System Repairs		
Parts cost (\$)	0.00	0.00
Labor hours	0.0	10.0
Total cost (\$)	0.00	500.00
Total cost (\$ per mile	0.00	0.00
Fuel System Repairs		
Parts cost (\$)	277.30	439.64
Labor hours	14.0	0.0
Total cost (\$)	977.30	439.64
Total cost (\$ per mile	0.07	0.00
Powerplant System Repairs		
Parts cost (\$)	522.32	1,063.86
Labor hours	124.5	11.5
Total cost (\$)	6,747.32	1,638.86
Total cost (\$ per mile	0.49	0.01
Electric Motor and Propulsion Repairs		
Parts cost (\$)	22.75	0.00
Labor hours	122.5	0.0
Total cost (\$)	6,147.75	0.00
Total cost (\$ per mile	0.44	0.00
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)		
Parts cost (\$)	689.40	1,388.99
Labor hours	1.5	23.3
Total cost (\$)	764.40	2,551.49
Total cost (\$ per mile	0.06	0.02
Air Intake System Repairs		
Parts cost (\$)	745.38	621.08
Labor hours	0.00	3.0
Total cost (\$)	745.38	771.08
Total cost (\$ per mile	0.05	0.01
Cooling System Repairs		
Parts cost (\$)	80.91	530.15
Labor hours	0.0	18.0
Total cost (\$)	80.91	1,430.15
Total cost (\$ per mile	0.01	0.01
Transmission Repairs		
Parts cost (\$)	0.00	485.48
Labor hours	0.0	6.5
Total cost (\$)	0.00	810.48
Total cost (\$ per mile	0.00	0.01

Roadcall Analysis

A roadcall (RC) or revenue vehicle system failure (as named in the National Transit Database) is defined as a failure of an in-service bus that causes the bus to be replaced while it is on route, or one that causes a significant delay in schedule. If the problem with the bus can be repaired during a layover and the schedule is maintained, then this is not considered a RC. The analysis provided here includes only RCs that were caused by “chargeable” failures. Chargeable RCs include systems that can physically disable the bus from operating while it is on route, such as interlocks (doors, air system), engine, etc., or things that are deemed safety issues if operation of the bus continued. Chargeable RCs do not include roadcalls for things such as problems with radios or destination signs.

Table 9 shows the RCs and miles between the roadcalls (MBRC) for each study bus categorized by all RCs and propulsion-related-only RCs. The diesel buses have much better MBRC rates for both categories. This fact is indicative of the low usage and prototype status of the fuel cell bus. Issues that caused propulsion-related RCs for the fuel cell bus are as follows:

- Traction batteries – 3
- Hybrid propulsion system – 5
- Fuel cell power system – 2
- Fire suppression system problem – 1

Table 2. Roadcalls and Miles Between Roadcalls (Evaluation Period)

Bus	Mileage	All Roadcalls	All MBRC	Propulsion Roadcalls	Propulsion MBRC	Fuel Cell Only MBRC
Total FCB	13,862	12	1,155	11	1,260	6,931
725	37,512	3	12,504	2	18,756	—
726	38,283	4	9,571	4	9,571	—
727	37,054	0		0		—
Total Diesel	112,849	7	16,121	6	18,808	—

What's Next for CTTRANSIT

CTTRANSIT plans to operate this fuel cell bus as long as possible although the agency's primary focus will transition to the new fuel cell bus project under the FTA's National Fuel Cell Bus Program (NFCBP). Under this project, CTTRANSIT will operate up to four new fuel cell buses from Van Hool and UTC Power. This is one of eight demonstration projects awarded as part of the NFCBP. The CTTRANSIT project was awarded through the Northeast Advanced Vehicle Consortium and UTC Power. The buses are part of a larger fuel cell bus order by AC Transit in Oakland, California (12 buses for California and 4 for Connecticut). The first of the new buses is expected to arrive in Connecticut in early 2010.

To prepare for the arrival of new fuel cell buses, CTTRANSIT has been working with the state to design and construct a new storage building at their depot. The funding for this new storage building has been secured, and the design is essentially complete. The project was put out for bid in mid-December 2009. The new construction is scheduled for completion by July 2010. This timeline means that the newer fuel cell buses will spend their first winter outside plugged into power from the main facility to keep the fuel cell systems warm. CTTRANSIT has recently installed plug-in cables at the back of the facility for this purpose.

CTTRANSIT has also secured funding through a DOE Clean Cities grant. Clean Cities annually funds cost-share projects submitted by its coalitions' public-private partnerships. During 2009, DOE Clean Cities selected 25 projects that will be funded with nearly \$300 million from the American Recovery and Reinvestment Act. Among the recipients, the Greater New Haven Clean Cities Coalition, Inc. received \$13,195,000 for the Connecticut Clean Cities Future Fuels Project. As part of this project, CTTRANSIT will build a new hydrogen station at the Hartford Division capable of dispensing 30 kg/day of hydrogen on-site in Hartford, Connecticut.

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Related Reports

All NREL hydrogen and fuel cell–related evaluation reports can be downloaded from the following Web site: www.nrel.gov/hydrogen/proj_fc_bus_eval.html.

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